

The ferrite-cored balun transformer

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Introduction

The ferrite-cored balun has been around for a long time now. The definitive paper appeared in 1959 [1], and *QST* gave a useful coverage in 1964 [2]. Many UK amateurs will be familiar with the G3HZP design which appeared in 1967 and subsequently in [3]. This article presents some comparative measurements on these and more recent developments [4, 5, 6] and identifies some of the crucial factors in balun construction.

Principle of operation

The modern ferrite-cored balun uses two principles over different parts of its frequency range. At the low frequency end it behaves as an ordinary transformer using a suitable core material. At the high frequency end it behaves as a length of transmission line. This behaviour is illustrated by the results in Fig 1 which show how the performance of a conventionally-wound auto-transformer falls off at high frequencies, whereas a transmission line transformer deprived of its core magnetization behaves well at high frequencies.

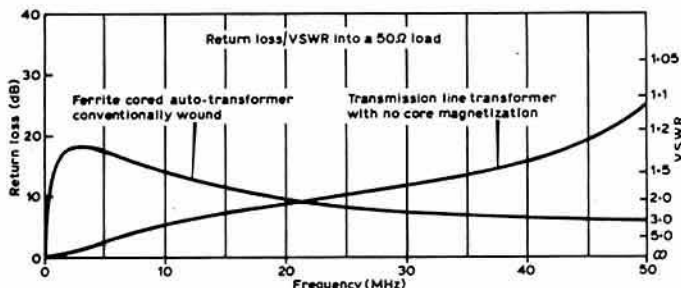


Fig 1. Illustration of the separate mechanisms in the broadband ferrite-cored balun

When these two separate mechanisms are combined in one transformer, wideband performance can be expected over a frequency ratio of as much as 200:1 or more. This makes the 20:1 required for the lowest seven amateur bands look quite modest.

Low frequency action

There are two winding configurations in frequent use; an auto-transformer and a two-winding type (Fig 2). For both types a toroidal core is normally chosen to give the highest achievable coupling between windings. This is desirable to keep the insertion loss of the finished transformer to an absolute minimum.

The choice of core material is, as ever, a compromise. High permeability cores require very few turns to produce a given inductance, and this keeps

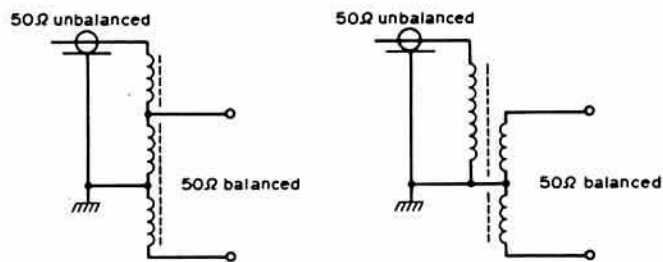


Fig 2. Two possible balun winding configurations

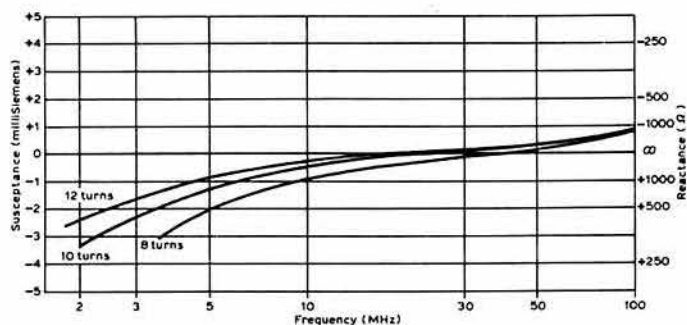


Fig 3. Curves showing the variation of susceptance/reactance of various coils wound on a pair of FX1588 toroidal cores

the electrical length of the windings down even at the hf end of the frequency range covered. This is important for effective "transmission line" action as will be seen later. Such high permeability cores have increasingly high losses associated with them as the frequency rises. Selection of a core suitable for the lower end of the frequency range only is needed (see Fig 1). The pair of stacked FX1588 cores used by G3HZP [3] is very suitable for amateur applications and has a performance very close to the Indiana General F-568-1 core of Q1 material used in many American designs.

Fig 3 gives a plot of susceptance against frequency for a pair of FX1588 cores with different windings. Parallel resonance of the winding inductance with the stray capacitance occurs when the susceptance reaches zero. The core is quite usable in this range until the net capacitive susceptance becomes high with the onset of series resonance of stray capacitance and leakage inductance.

The next question is just how many turns are actually necessary. Consider the low frequency equivalent circuit of a 1:1 transformer in Fig 4. If the design is reasonable R_1 and R_2 will be very much less than 50Ω , while R_c will be much greater than 50Ω . So the components of importance are the primary inductance L_p and the load resistance seen through the "ideal" transformer. This situation is illustrated in Fig 5. The current in the primary inductance serves to magnetize the core which is essential for transformer action to occur. If the primary has too few turns the magnetizing current I_m will be excessive and will cause serious shunting of the load. Notice that I_m and I_l are in quadrature, and Figs 6 and 7 show how the shunting is not quite as serious as one might expect. Keeping the primary inductive reactance at five times the load resistance results in negligible current shunting.

However, there is one other aspect. It is not unreasonable to expect the finished balun to work over a limited range of load vswr—say up to 2:1. This can mean a load resistance as high as 100Ω , so a primary inductive reactance of the order of $400\text{--}500\Omega$ is required. Referring to Fig 3, 12 turns on a pair of FX1588 cores will provide this order of inductance down to 1.8MHz . Fewer turns can be used if a low-end cut-off is required at a higher frequency. However, the bandwidth of the finished transformers is so large as to hardly make this worthwhile.

Tests

A word now about the tests that were carried out. Swept measurements were made using a spectrum analyser, tracking generator and reflection bridge. These enabled measurements of, return loss to be made. Return loss is an alternative measurement to vswr. When a signal is reflected from a mismatched load, only a portion of the incident signal is reflected. The apparent loss of the reflected signal compared to the incident signal is called the return loss

$$\text{Return Loss} = 20 \log_{10} \left(\frac{\text{Incident signal voltage}}{\text{Reflected signal voltage}} \right)$$

If the load is a complete mismatch ($\infty:1$ vswr) the reflected voltage equals the incident voltage and the return loss is 0dB. A return loss exceeding 20dB ($<1/10$ of the incident voltage being reflected) represents a pretty good

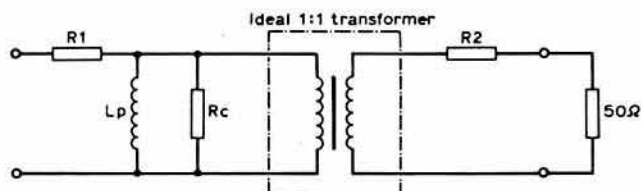


Fig 4. The low frequency equivalent circuit of a transformer. R_1 is the series loss resistance of the primary; R_2 is the series loss resistance of the secondary; R_c represents the core losses; and L_p is the inductance of the primary

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Fig 5. The shunt current path for I_m produced by inadequate primary inductance

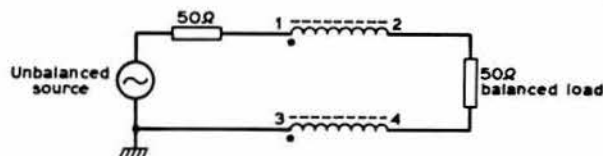
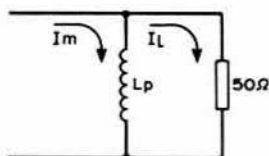


Fig 10. A simple transmission-line balun transformer

The low frequency performance is adequate up to about 10MHz, but progressively worsens at higher frequencies. Even more revealing is the result for 25Ω and 100Ω loads (Fig 9). The two results should be identical and equal to a return loss of 9.6dB plus twice the insertion loss. Below 7MHz the results are reasonable, but there is a growing disparity above this frequency. To be fair, the transformer tested had been optimized for use on the lower frequency bands by the use of 12 instead of 10 turns on each winding.

The transmission-line transformer

A simple type of balun transformer recommended by some beam antenna manufacturers consists of a dozen or so turns wound in the coaxial feeder and positioned close to the antenna feedpoint. This is a form of the transmission-line balun and is illustrated in Fig 10. Both ends of the load are isolated from earth by the reactance of the windings, and either end or the centre of the load may be earthed. Most of the stray capacitance will be absorbed into the characteristic impedance of the line, and it is this feature which greatly extends the hf performance. The equal and opposite currents flowing in the two "legs" of the transmission line cancel core flux and hence minimize core losses. This is useful because the core selected for good lf performance is likely to be very lossy at the hf end. The length of the transmission line used must be kept below $\lambda/5$ at the highest frequency [1, 7] otherwise the phase shift in the line section can cause partial cancellation of the output signal.

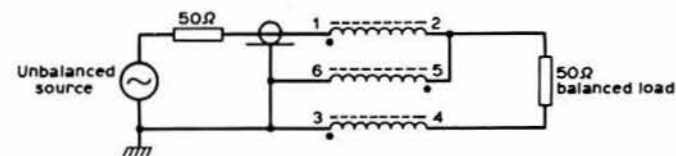


Fig 11. A transmission-line balun transformer with added "compensating" winding

The major problem with this type of balun is the provision of a core magnetizing current path to facilitate good low frequency action; [5] also shows the inferior balance performance of this simple arrangement. The solution is to provide a "compensating" winding which, at low frequencies, makes the transmission line arrangement of Fig 10 equivalent to the autotransformer arrangement of Fig 2. The circuit of a balun of this type is drawn in Fig 11, and the dot notation is used to denote the start of each winding. Great care must be taken to get the sense of the windings correct, as it is easy to get confused. Indeed, in one of the references quoted, a diagram appears of a balun with an incorrectly-connected compensating winding causing cancellation of the core flux at low frequencies.

The magnetizing current can now flow from terminals 1-2 then 5-6 in Fig 11. The balance of this circuit is also very good, and it represents the basic arrangement of the remaining baluns tested. For best results the characteristic impedance of the transmission line should be the same as the input/output impedance—in this case 50Ω; [8] shows that 22swg enamelled wire twisted to about one or two twists per centimetre has a characteristic impedance of around 50Ω.

Transmission-line balun tests

One of the first baluns tested consisted of a trifilar twisted winding of 1mm diameter wire on a pair of FX1588 cores. Six turns were wound because the series connection of two of the windings across the input allows the magnetizing current to flow through a total of 12 turns. This transformer was among the best tested, and is shown in Photo 2. Fig 12 shows the vswr/return loss into 50Ω, and Fig 13 the results with 25Ω and 100Ω loads. The vswr into a 50Ω load is at the limits of the accuracy of the load used over most of the frequency band. This represents very good performance, but the one limiting factor is the voltage rating of the tightly-twisted enamelled wire used. This raises serious doubts about the power rating of this transformer.

Before leaving the trifilar design, another experimental version was constructed using loosely-twisted 1.5mm stranded wire with thick pvc insulation. The results were most disappointing and emphasized the need

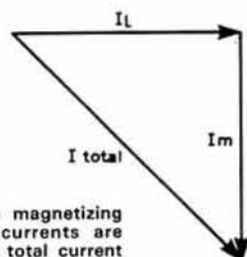


Fig 6. The magnetizing and load currents are equal. The total current drawn is $\sqrt{2}$ times that drawn by an ideal transformer

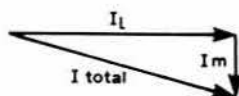


Fig 7. The magnetizing current is now one-fifth of the load current. The total current drawn is now only two per cent more than that drawn by an ideal transformer

Phasor diagrams Figs 6 and 7 illustrate the shunting effects of the magnetizing current

match by amateur standards, equivalent to a vswr of 1.22:1 or better. The graphs have their vertical axes marked in terms of both return loss and vswr for ease of reference.

The baluns tested were terminated in a balanced 50Ω load (visible in Photo 1). This was capacitively compensated at 50MHz, and represents a reasonably accurate load by amateur standards. The return loss/vswr seen from the unbalanced side of the transformer should be good over the desired frequency range.

A second test was to terminate the balun with, first, a 25Ω load, and, second, with a 100Ω load. Clearly, both of these should result in a vswr of 2:1 or a return loss of 9.6dB assuming zero transformer insertion loss.

Insertion loss was tested by connecting two identical transformers back to back to give UNBAL → BAL → UNBAL, and connecting the combination between the tracking generator and the spectrum analyser. Finally balance measurements were made by observing the variation of voltage at the centre tap on a 50Ω load.

Tests on a conventionally-wound balun

The first transformer tested was the G3HZP balun used by the author for many years on a variety of 1.8 and 3.5MHz dipoles. This is representative of the non-transmission line type of balun, using a bifilar winding technique with separate primary and secondary windings. This is apparent from Fig 8, which shows the vswr/return loss when the transformer feeds a load of 50Ω.

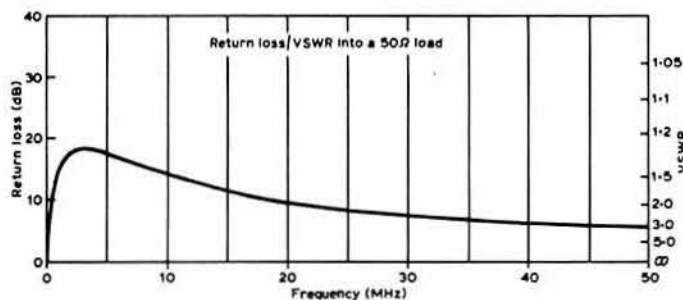


Fig 8. The G3HZP balun

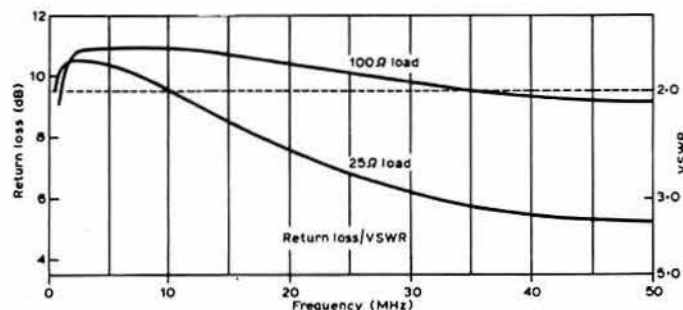


Fig 9. The G3HZP balun into a 2:1 load vswr

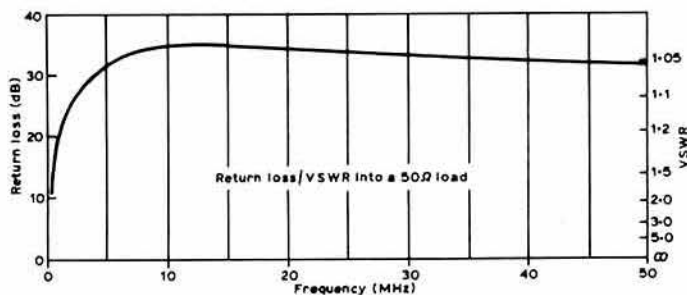


Fig 12. Balun wound with trifilar 1mm diameter wire

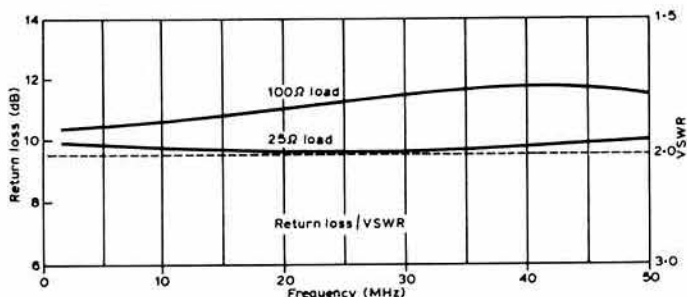


Fig 13. Trifilar wound balun into a 2:1 load vswr

for tight coupling between the trifilar windings to make them as nearly identical as possible and all subject to the same flux linkage.

Coaxial cable may be utilized for the transmission line used for windings 1-2 and 3-4 of Fig 11. This has the advantage of a much improved working voltage and a better guarantee of the characteristic impedance. The compensating winding is an additional piece of enamelled wire wound as shown in Fig 14. Results for this balun are shown in Figs 15 and 16. Balun A was wound with the compensating winding taped at intervals of about 4cm to the coaxial cable, while balun B was wound with the compensating winding and the coaxial cable fixed together with heat shrink sleeving to give the tightest possible coupling. Once again the importance of tight coupling between the windings is obvious from the results. Photo 1 shows two completed baluns of type B made with 1mm diameter compensating winding and UR76 and RG174 coaxial cables respectively. To wind the six turns required onto a pair of FX1588 cores, about 400mm of sleeved cable is needed. This assembly is shown at the top of Photo 1.

Swept measurements on the UR76 version of balun B show the insertion loss to be reasonably flat. Measurements on two baluns back to back using

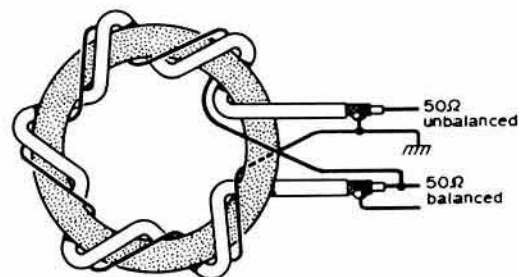


Fig 14. Balun wound with coaxial cable and a "compensating" winding

an rf millivoltmeter gave the loss as 0.15dB at 1.8MHz, rising to 0.2dB at 28MHz. With such low losses accurate measurements are not easy to make, but the low values obtained are most encouraging. Balance is also very good over the range 1.8-30MHz.

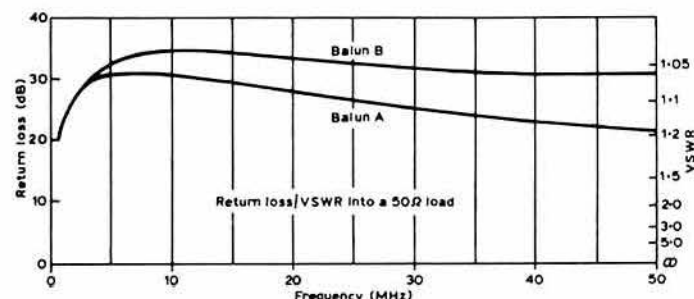


Fig 15. Performance of baluns wound with coaxial cable and a compensating winding

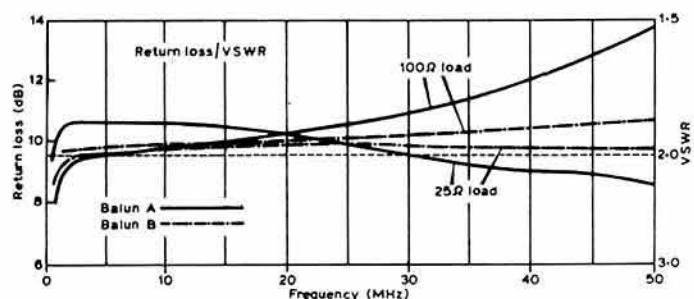


Fig 16. Baluns A and B into a 2:1 load vswr

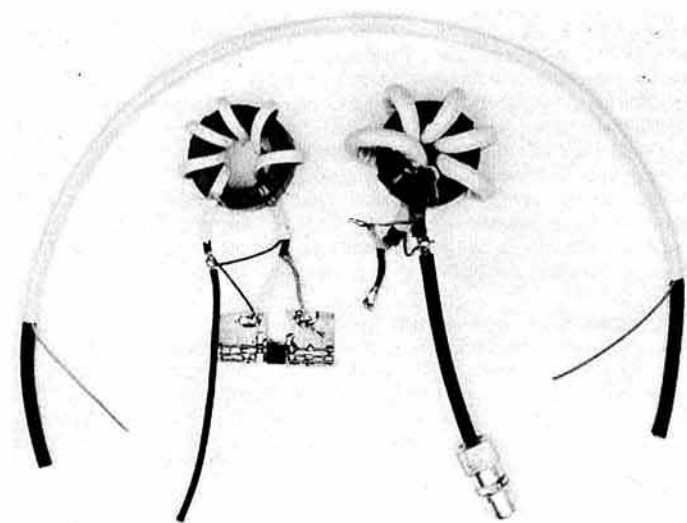


Photo 1. Completed baluns wound with a coaxial cable and compensating winding. The transformer on the left is wound with RG174 and is shown connected to the 50Ω balanced load. The right-hand transformer uses UR76, and both transformers use 1mm enamelled wire for the compensating winding. Around the edge of the photograph is a length of UR76 and 1mm enamelled wire fixed together with heat-shrink sleeving prior to winding

"Super toroid" technique

T. A. O. Gross [9] first suggested an ingenious way of reducing the unwanted effects of self-capacitance in a toroidal core. This involves putting on half the winding, then crossing to the opposite side of the core adjacent to the start and continuing to wind with the same sense. Fig 17 shows this technique. It has the effect of keeping the two points with the greatest potential difference away from each other and hence reduces the current in the stray capacitance. References [5] and [6] discuss the application of this technique to balun construction.

Care must be taken not to get over-enthusiastic about this technique, since the transformers already described are capable of excellent performance over the hf band. The requirement for close coupling between windings

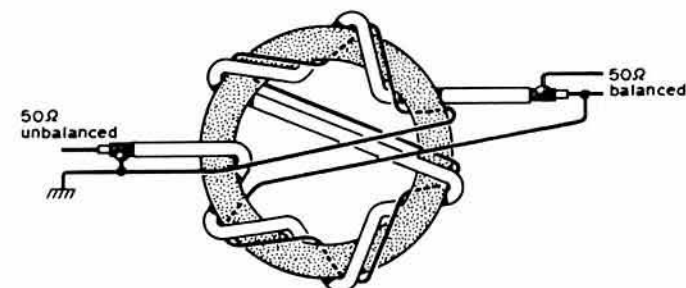


Fig 17. Balun wound using the "super toroid" technique

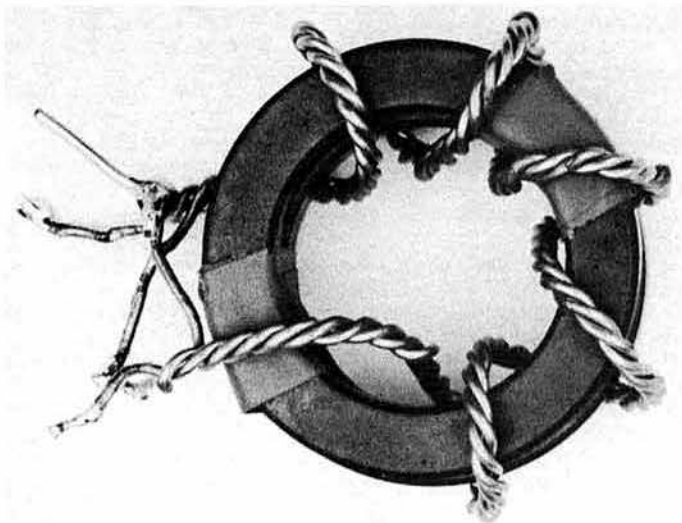


Photo 2. A trifilar-wound transformer utilizing three 1mm enamelled conductors on a pair of FX1588 cores

previously identified is paramount, and the inclusion of the compensating winding does nullify some of the advantage of Gross's technique. Tests were carried out on a balun of this type and the results appear in Figs 18 and 19. These show little difference from the conventionally wound baluns of Figs 14, 15 and 16.

Power handling

Tests were carried out on a pair of the type B transformers described above. The two identical transformers were connected in series between a transmitter and a dummy load, to give a 50 Ω unbalanced-50 Ω balanced-50 Ω unbalanced sequence. Measurements were made of temperature rise and the level of the third-order intermodulation products with 400W p.e.p. applied. The temperature measurements were singularly unexciting, as a rise of less than 0.1°C was recorded for core and winding surface temperatures after 5min of continuous operation.

The effects on intermodulation were much more significant and reveal the greatest single disadvantage of the ferrite-cored balun transformer. At 28MHz the balun behaves as a true transmission line transformer, and Figs 20 and 21 show the output spectrum (10dB/div vertically and 1kHz/div horizontally) with and without the baluns in circuit. The differences are barely discernible and the third-order i.m.p. suppression is about 25dB in both cases. Figs 22 and 23 show the results of the same test carried out at

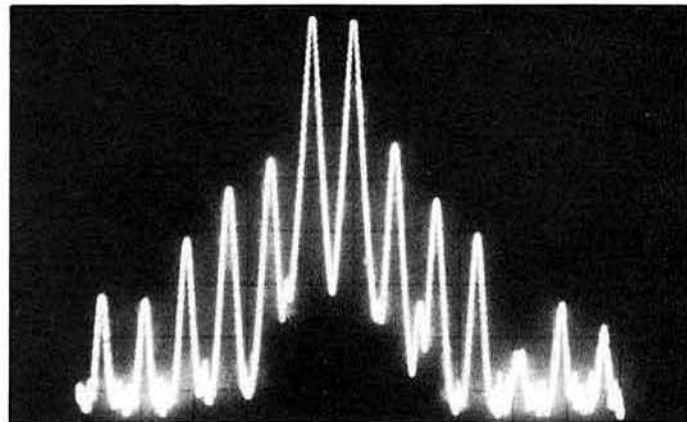


Fig 20. Intermodulation distortion produced at 28MHz 400W p.e.p. with baluns

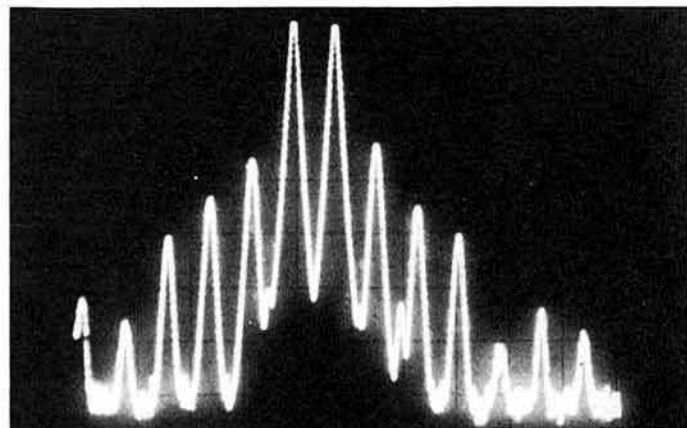


Fig 21. Intermodulation distortion produced at 28MHz 400W p.e.p. without baluns

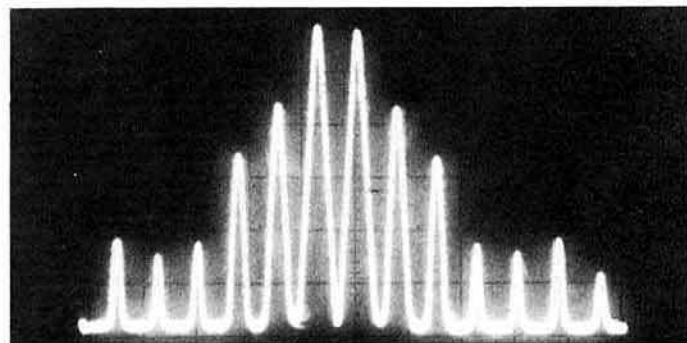


Fig 22. Intermodulation distortion produced at 3.5MHz 400W p.e.p. with baluns

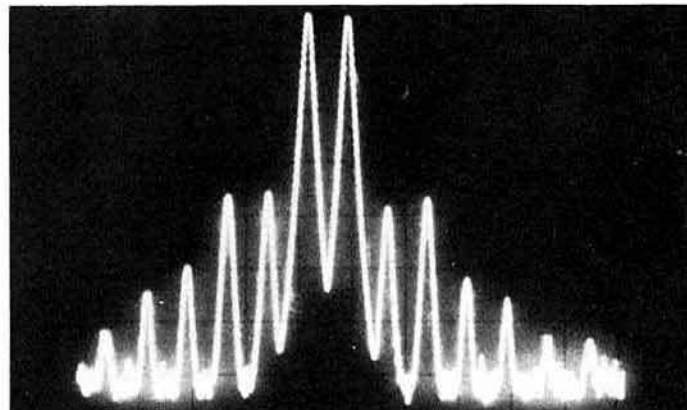


Fig 23. Intermodulation distortion produced at 3.5MHz 400W p.e.p. without baluns

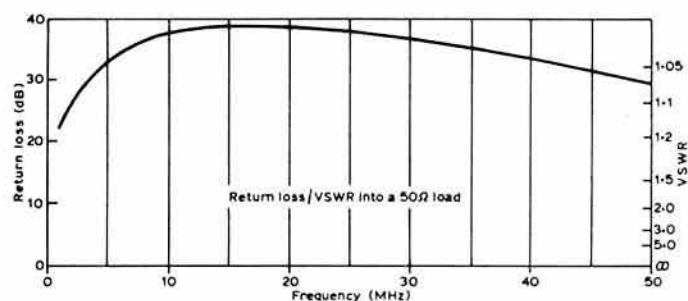


Fig 18. Performance of the balun wound using the "super toroid" technique

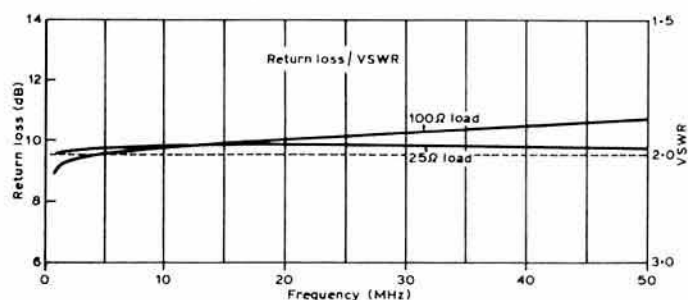


Fig 19. "Super toroid" balun into a 2:1 load vswr

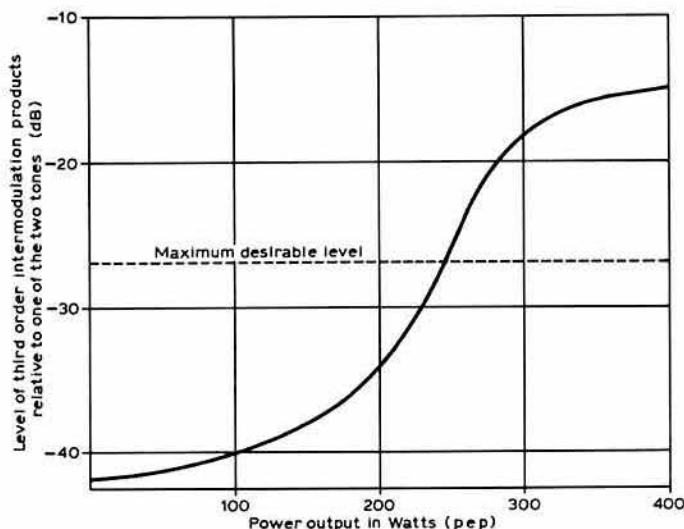


Fig 24. Graph of the level of third-order i.m.d. against p.e.p. output on 3.5MHz for two balun transformers of type B

3.5MHz and here the effect of the balun is quite dramatic. The third-order i.m.p. suppression worsens from -34dB to a mere 15dB. This behaviour is in line with the dominant action of the ferrite core at low frequencies and shows that unacceptable intermodulation distortion can occur even when the temperature rise is imperceptible.

Reducing the output level produced a more satisfactory state of affairs. The graph in Fig 24 shows how the level of third order imd varies with power transmitted through the balun. Remember that these results are for *two* transformers, and one alone could be expected to show an improvement of 3dB.

Finally, a word about encapsulation. This is necessary for weather protection, but remember that conducting surfaces close to the transformer will degrade the excellent performance obtained. Diecast boxes make good weatherproof enclosures when the lid joint is smeared with gasket goo, but choose one large enough to keep the transformer away from the walls. Photo 3 shows such an arrangement—note the use of plastic foam to keep the transformer clear of the walls. A more compact encapsulation would be possible using insulating materials. ABS boxes or plastic drainpipe seem good candidates here.

Conclusion

The tests carried out verified the excellent performance of the balun made with a length of coaxial cable and a "compensating" winding. The importance of closely-coupling all the windings, and the power handling limitations due to intermodulation were highlighted. Transformers of this type can give good performance across all the hf bands, and there is no need to optimize the design for any one group of bands.

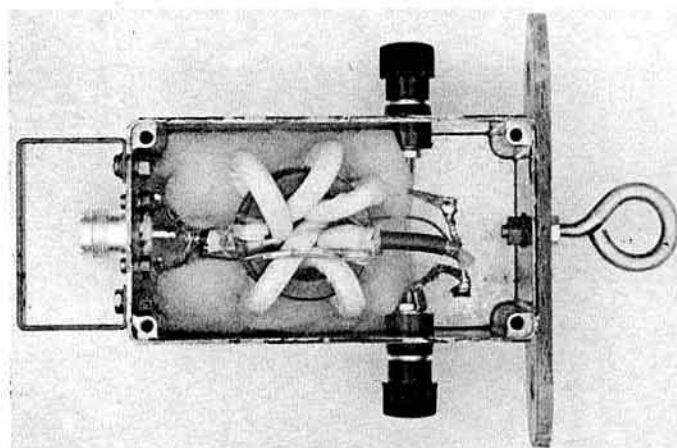


Photo 3. The completed "super toroid" balun encapsulated in a diecast box. Note the use of a suspension eye, an SRBP dipole wire terminating strip, and a support bracket to prevent the weight of the coaxial feeder being taken by the PL259 plug

References

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A note on overvoltage protection

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SOLIDSTATE TRANSCEIVERS designed for mobile use are commonly meant to operate from a supply of nominally $13.5V \pm 10$ per cent. The operating manual may specify a maximum voltage of perhaps 15V, and operating a transceiver at more than this maximum may result in damage—perhaps very expensive damage.

While building a low-voltage supply capable of giving 10 or 12A with good regulation presents its own problems, many units from which the common 10W transceiver is operated must have been built. Commercial units in this current class sell in the £20 plus price range.

Typically, low-voltage power packs operate by sampling the output voltage, comparing it with a reference voltage, and using the output to control a series transistor through which the entire current to the transceiver or other equipment must flow. The principle is shown in Fig 1. The device which compares V_{ref} with a sample of V_o and in turn controls the pass transistor TRL, may be a purpose designed ic, an inexpensive op-amp like the 741 or, with some circuit changes, a low-power transistor like the BFY50 series may be pressed into service. The reference voltage may be derived "on chip" or from an external zener diode. For correct operation the voltage at the collector of TRL must be greater than the required output voltage.

Measurements on a widely-advertised commercial unit used by the author showed that the output voltage was 14.2V but the voltage at the collector of the series pass transistor was nearly 30V with no load. One does not need a very vivid imagination to appreciate the effects of a collector-emitter short-circuit putting the full unregulated supply across the power leads of the transceiver. The power supply in question claimed to be fully protected against overload, but when the lid came off it was clear that this meant only that it would current limit at about 4A. No attempt was made to protect against an overvoltage at the output.

When an overvoltage fault condition is detected the power supply must be instantaneously and automatically disconnected from whatever equipment it is powering if damage is to be prevented. A crude but very effective way of doing this is, in effect, to short-circuit the output to the power supply and thus blow a fuse in the supply line. For convenience the fuse should be able to carry slightly more current than that at which the supply limits, or if

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